1998

Fine coal dewatering by compaction in bins exhibiting reliable discharge

A. G. McLean

Fine Coal Dewatering by Compaction in Bins Exhibiting Reliable Discharge

A G McLean[1]

ABSTRACT

This paper firstly reviews the requirements for container and hopper design for reliable discharge. Discussion is then directed to the evaluation of the consolidation stresses acting in both in both the cylinder and hopper sections during both initial and flow conditions. Here the vast difference, especially in vicinity of the bin outlet, between the initial or filling and flow conditions is highlighted. This vast difference has major design and operation implications. A further major implication is that all bulk solids must dilate to flow. The opportunity to simultaneously attain reliable discharge and partial moisture removal is also examined.

The selection of design parameters to maximise the consolidation stresses in both the cylindrical and hopper sections is detailed. In regard to the latter, it is recommended fine coal bins be discharged using low friction lined transition hoppers with large outlet spans. Such outlets will discharge fine coal in a relatively compacted state. This compaction state should exhibit minimum water retention and short term moisture uptake.

The multiphase attributes of fine damp coal flow is then considered. Here is it noted, as a consequence of the dilation in the hopper negative or suction interstitial fluid pressures form. It is noted such pressures generate an adverse pressure gradient which significantly retards the discharge. One technique to conveniently eliminate the adverse pressure gradient is to install low pressure high volume air sparging to the hopper. It is suggested this air sparging will have the added benefit of effecting partial moisture reduction. This technique should prove far more reliable than post feeder compaction using relatively complex mechanical systems.

INTRODUCTION

General

To date fine coal bin storages have been largely designed to achieve maximal storage capacity at minimal cost. Such bin storages have resulted in generally adverse bin operation characterised by relatively small live storage capacity and unreliable discharge or in extreme cases complete flow obstructions. To allay these operation deficiencies greater attention has been devoted to designing bins for reliable discharge. This reliable discharge is possible by applying the principles of modern bulk solids handling design. However, due to increased economic pressures coal producers are increasingly faced with the problem of storing increasingly finer and wetter coal into bin storages (typical of larger capacity). Furthermore their customers are demanding dryer coal exhibiting favourable flow properties. Noting the coal industry is faced with these acute demands, it is appropriate to examine the design and operation of coal bins to simultaneously effect both reliable discharge and partial dewatering of fine coal products including fine reject material. The possibility of achieving these seemingly counter opposed goals will first be discussed in reference to gravity discharge bins. This initial discussion will highlight that reliable discharge of fine wet coal requires proper attention to the multiphase nature of the stored material and awareness that all particulate materials must dilate to flow in and more importantly from converging channels. The same will also highlight that existing bin designs generate minimum opportunity for simultaneous dewatering and reliable discharge. In fact it will be shown that some existing bin geometries completely overlook the opportunity to effect partial dewatering simultaneous to reliable discharge. Discharge from such bins, when compounded by poor operation practices, typically exhibits high moisture content. Most notable of such situations is rainfall collection in partially discharged funnel flow bins. On the contrary it will be shown

Department of Mechanical Engineering, University of Wollongong,

that partial dewatering is possible by installing air sparging systems into fine coal storages. The latter part of the discussion will highlight the potential of bin feeder system designs to effect both reliable discharge and partial dewatering.

- In this discussion typical bin geometries will be adopted namely a bulk solid container comprising a cylindrical section atop a converging section, Fig. 1. The latter converging section may be either of axisymmetric or planar form. It is also expected the reader is familiar with the concept of mass flow channels. Such channels are now appropriately much used because of their superior flow characteristics (Arnold et al, 1981), especially when storing and discharging fine cohesive coal.

In regard to dewatering, it is expected water will be displaced from the interstitial particle spaces whenever the particulate bed is subject to high consolidation pressures with decreasing interparticle spacing. On the other hand a solids bed is referred to as dilating whenever the interparticle spacing is increasing. Such dilation occurs when bulk solids experience decreasing magnitude consolidation stresses.

Requirements for reliable discharge

Reliable discharge of fine coal from a converging channel or hopper requires:

- the flowing coal is yielding throughout the bulk
- slip is occurring along the walls
- existence of an arched stress field (Arnold et al, 1981)
- opportunity for the flowing bulk solid to dilate
- the magnitude of the gravity generated body forces must exceed any interstitial fluid phase adverse pressure gradients (Reed,1973; Johanson, 1979;McLean, 1984) .

- Fortunately, procedures now exist to design converging channels to generate reliable discharge of cohesive bulk solids subject to (near) incipient flow conditions. Basically design of the hoppers for reliable design involves selecting (Arnold et al, 1981):
    - the outlet span (B) to be sufficiently large to cause collapse or yielding of the cohesive bulk
    - selecting the hopper wall slope (α) to be sufficiently steep to attain slip along the walls
    - hopper walls with low sliding friction characteristics
    - hopper details to ensure the transport volume increases in the direction of flow (ie diverging feeder side skirts, flow regulation gate stress relief, provision of overhangs at joint lines, etc.).

CONSOLIDATION STRESSES IN BINS

General

Equations for predicting the consolidation stress variation with depth in typical bins or bulk solid containers for both initial and flow conditions are now well known(Arnold, 1981). Such variations, for a typical bin geometry, are depicted in Fig. 1.

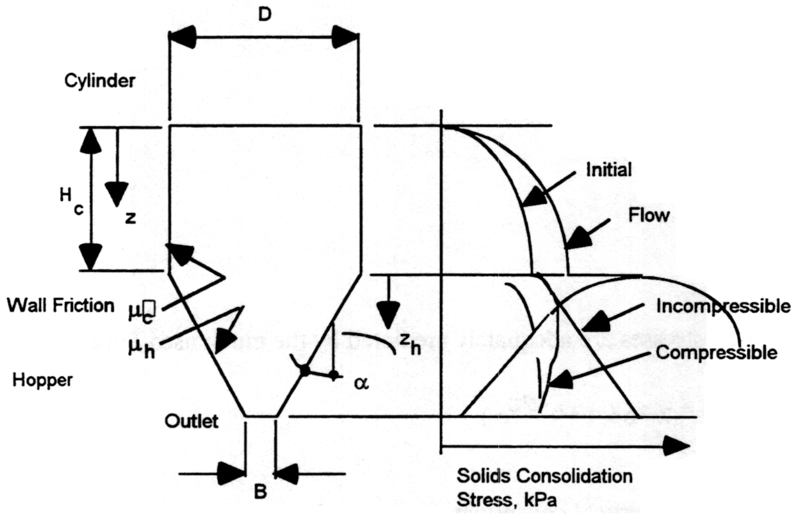

Fig. 1 - Typical bin geometry depicting initial and flow consolidation stress variations

Parameters Governing the Extent of Consolidation in Bins

It can be well appreciated that the magnitude of the consolidation stresses to which the flowing bulk solid is subject depends on:

- solids bulk density and compressibility noting for fine coal the variation of bulk density with consolidation is adequately described by

$$\theta = \theta_0 \left(\frac{\sigma_1}{\sigma_{1o}}\right)^b \qquad (1)$$

or in terms of specific weight χ

$$\chi = \theta g \qquad (2)$$

where

θ	bulk density, kgm^{-3}
θ_o	characteristic empirical bulk density at stress level σ_{1o}, kgm^{-3}
ρ_1	major consolidation stress, kPa
ρ_{1o}	empirical major consolidation stress, kPa
b	empirical exponent, -
χ	bulk specific weight, kNm^{-3}
g	gravitational acceleration, 9.81 ms^{-2}

- internal friction angle (δ)
- boundary friction angle (ϖ_w)
- cylinder diameter (D)
- cylinder height (H_c)
- form of the channel (ie whether axisymmetric or planar flow)
- stress field factor (K)
- whether the bin contents are inactive (filling, initial or peaked) or active (flow or arched)

- the time of storage
- bulk solid moisture content
- solids and fluid phase specific gravities
- permeability to fluids flow

Cylinder consolidation stresses

In the cylinder the consolidation stresses are adequately predicted by the much used Janssen variation given by

$$\rho_1(z) = \chi\, z_0\, (1 - e^{-z/z_0} \qquad (3)$$

where

$\rho_1(z)$	the major vertical consolidation stress, kPa
z_0	parameter defined by z_0 = D/4□K_j
D	channel inscribed diameter, m
λ	boundary friction coefficient = tan □$_w$
ϖ_w	boundary Coulomb friction angle,°
K_j	stress field factor relating the orthogonal stress components
z	depth from the effective surcharge level, m

An examination of equation (3) suggests the consolidation stresses are large whenever the cylinder variables χ, H & D are large and ϖ_w is small.

Consolidation stresses in hoppers

Since most bin storing fine coal involve a combination of a cylinder atop a hopper or converging section it is appropriate to examine the consolidation stress variation with depth. Obviously this much used arrangement facilitates convenient concentrated discharge, usually through a central symmetrical outlet, of the contents to downstream unit processes. However, much to the surprise of most coal operators, whenever a converging channel is used to discharge bulk solids the stresses acting on the discharging material in the vicinity of the hopper outlet are low in magnitude (typically 3 - 10 kPa) as shown in Fig. 1. In fact the variation in the consolidation stresses in the converging section of a bin is adequately described by equation 6.3.5(3) in (SAA, 1996) namely:

$$\rho_1(z_h) = K \frac{\gamma(h_h - z_h)}{(j-1)} + [\, p_{vit} \quad \frac{\gamma h_h}{(j-1)} \quad (\frac{(h_h\text{-}z_h)}{h_h})^j \qquad (4)$$

where

$$K = 0.5*(1+k_{hf})\,(1 + \sin(\delta)) \qquad (5)$$

and

$\rho_1(z_h)$	consolidation stress at depth z_h in the hopper, kPa
h_h	height of the hopper from the apex to transition, m
z_h	depth below the cylinder to hopper transition, m
γ	unit weight of bulk solid, kNm^{-3}
p_{vit}	container transition mean vertical pressure, kPa
j	stress field parameter, defined in Clause 6.3.5 (SAA, 1996)
k_{hf}	normal pressure ratio for hopper based on powder mechanics principles
δ	effective angle of internal friction,°
α	hopper angle, °

For initial conditions in the hopper it may be noted the stress field parameter j exhibits a magnitude less than unity and in fact approaches zero when incompressible bulk solids are stored in channels exhibiting minimal boundary flexibility. On the other hand during flow j is large and positive with typical values exceeding 3. Such values for j cause eqn (4) to reduce, in the vicinity of the hopper outlet, (ie for z_h large) to

$$\rho_1(z_h) \propto K \{ \frac{\gamma(h_h - z_h)}{(j-1)} \qquad (6)$$

Equation (6) predicts the well known radial stress field variation for converging channels. It is now appropriate to examine the implications associated with eqn (6). The most significant implications, relating to the magnitude of the consolidation stresses at the outlet of a converging channel during flow are:

- strong dependence on the outlet span, B, (ie $B = 2 (h_h - z_h) \tan(\alpha)$;
- relative independence of the extent of consolidation effected in the container cylinder;
- strong dependence on the local magnitude of the bulk density;
- strong dependence on local channel parameters via the factor j including wall slope (α), wall friction (λ_h), channel form ie planar or axisymmetric (via factor c_h in SAA(1996) and a lesser extent on the effective angle of internal friction (δ).

OPPORTUNITY FOR PARTIAL DEWATERING AND COMPACTION

Cylinder

The existence of large consolidation stresses in the vertical bin section suggests the possibility to compact the bulk solid andhence mechanically remove some water from the same by installing suitable permeable walls in the vicinity of the cylinder hopper transition as depicted in Fig. 2. However, to date this opportunity has largely being ignored due to the hitherto unavailability of suitable low cost porous non blinding materials, high capital cost and for other reasons. However, the increased availability of sintered low friction wear resistant porous material suggests increased opportunity now exists to exploit this gravitational consolidation for dewatering. It may be noted the actual quantity of water removed would be dependent on the time of storage and be promoted by application of low magnitude vacuum pressure differentials across the permeable membrane. It may be noted since the permeability to water flow decreases with increasing depth in the cylinder it is usual to observe upward moisture migration (provided the particle density exceeds that of the fluid phase). In cases involving storage of extremely wet coal installation of bin top surface drainage facilities may also be warranted.

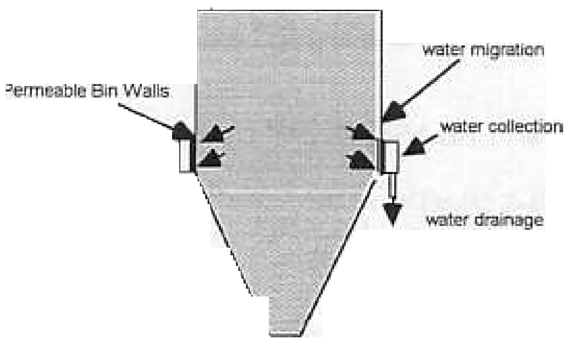

Fig. 2 - Dewatering using permeable bin walls at the bin transition

The existence of the large consolidation stresses at the base of cylindrical containers further suggests the opportunity for dewatering using live bottom bin arrangements as depicted in Fig. 3. To date such bin arrangements have received minimal application due to high capital cost and maintenance difficulties. A number of operation concerns have been allayed somewhat with the current generation of live bottom bin discharge units. In these arrangements the actual moisture reduction would be effected via permeable membranes situated in the container base. The extent of actual water removed or minimal water uptake on discharge may also be enhanced by incorporating a compaction zone at the discharge end of the extraction device.

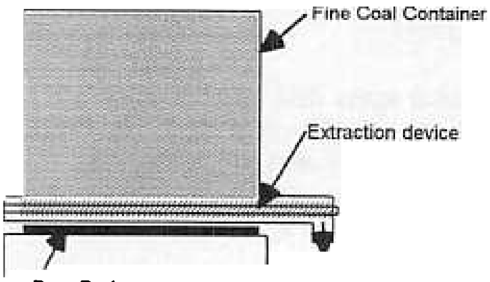

Fig. 3 - Live bottom bin storage and dewatering system

Typical bin cylinder hopper combination

Regarding the channel form, it is found planar channels (as a result of their more favourable flow characteristics (Chamberrlain, 1986)) generate stresses approximately double those occurring in axisymmetric channels (Arnold et al., 1981).
Noting this compaction of discharging fine coal can be maximised by utilising transition hoppers with large outlet spans. With the availability of wide belt or apron feeders such arrangements, refer Fig. 4, should receive increased application for handling fine coal products and delivering the same in relatively compacted states. Necessary design details for wide large capacity belt feeders are presented in the papers by Winkler (1973) and Bridge and Carson (1987).

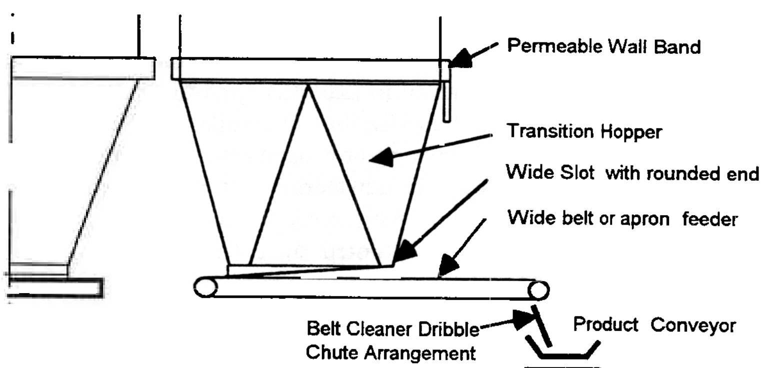

Fig. 4 - Schematic of a typical transition hopper wide slot feeder combination

MULTI PHASE FLOW CONSIDERATIONS

A further implication of equations (2) & (4) is that all bulk solids must dilate to flow. In fact this dilation of the hopper contents, in the case of bins with poorly selected hopper design parameters, may completely nullify the compaction effected to the bulk in the cylinder section. A further consequence of this dilation and the low permeability, especially to water flow of fine coal, suction interstitial pressure occur within the hopper during flow 3, 4, 5, 7 & 8]. Such suction or vacuum pressures, refer Fig. 5 severely retards the flowing bulk to the extent flow obstructions occur.

The actual extent of retardation can be accessed by considering the flow as subject to an effective gravitational acceleration (g*) (McLean, 1984 and Carson, 1987) of magnitude defined by

$$g^* = g_a ! \frac{1}{r}\frac{dp_f}{dz_h} \qquad (7)$$

where g_a is the actual gravitational acceleration (9.81 ms^{-2}), □□the bulk density of the flowing solid and dp_f/dz_h the local interstitial pressure gradient.

A not so obvious implication of equation (7) is that for low density bulk solids even a low magnitude adverse pressure gradient will cause
cessation of flow. Sluggish flow is also observed whenever fine low permeability bulk solids are discharged from bins with impermeable hopper walls. Here it is considered inappropriate to commit further discussion to the evaluation of the interstitial pressure gradient. However, it is most appropriate to consider what techniques can be employed to eliminate the existence of adverse interstitial gas pressure gradients.

The simplest and possibly the lowest cost technique is to supply low pressure high quantity aeration to the hopper contents (Lobb, 1995 and Lazzari, 1991) as opposed to supplying product deteriorating water injection). The extent and pressure of the aeration should be sufficient to generate a gradually varying monotonic pressure distribution exhibiting a favourable pressure gradient at the hopper outlet as shown in Fig. 6. In addition to effecting flow promotion this aeration or air sparging has the potential to simultaneously effect moisture reduction. The extent of this moisture reduction can be enhanced by preheating the air flow (particularly in situations where waste heat is available), increasing the air volume and increasing the air to coal contact time. Here the effetive contact or residence time may be increased by effecting recycling of the hopper contents. A further advantage of recycling is the maintenance of the bin, especially the hopper, contents in an activated state. In this activated state passive or arched stress fields are maintained in the vicinity of the hopper outlet.

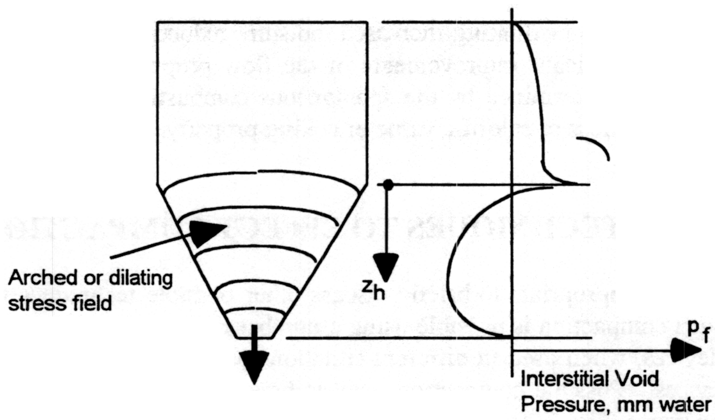

Fig. 5 - Interstitial void pressure variation generated during discharge of fine damp bulk solids

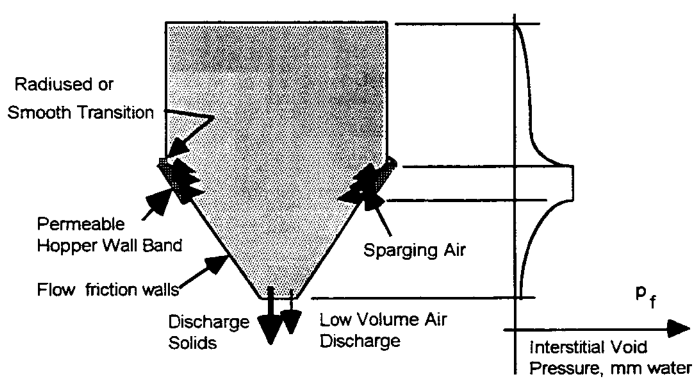

Fig. 6 - Air sparging during discharge to supply necessary dilation volume and effect moisture reduction

Here it should be noted the air sparging must be effected using low pressure high volume air supply during discharge. In no case should expensive high pressure high volume air supply be used as ratholes or air channelling will simply occur within the coal mass and in most cases coal flow will cease. It is usually most convenient to locate air injection devices at or immediately below the hopper transition. It should be noted air injection without bin dispatch is largely ineffective due to the high consolidation stresses applied to the hopper contents. Notably the applied consolidation stresses, during initial or filling conditions, causes the permeability of the hopper contents to be exceedingly low. This more or less eliminates low pressure air permeation through the same. The extent of air sparging may be increased by supplying the additional air via internal hopper fitments in combination with a wall permeation shelf or band. Even under the worst case scenario where the majority of air flow short circuits some beneficial moisture reduction would be effected along the actual and some what limited coal air interface. Here it may be noted use of internal hopper fitments ie hopper in hopper arrangements or inverted cone inserts also exhibit a flow promoting effect.

It must be noted here it is not the intention to completely fluidise the hopper bin contents as such fluidisation is grossly expensive as both the pressure and volume of the supplied air are large in magnitude. Such air supply variables contrast markedly to dilation air parameters. As one expects the air flow through the hopper contents under low intensity aeration would highly non uniform. This spatial variation results from the fact the air flow, in cohesive damp particulate beds, occurs essentially via channels formed in the bed and along boundaries of adjacent cohesive shear blocks. It is expected the bulk density of the actual shear blocks so formed would remain relatively high in response to the maximum consolidation experienced by the flowing coal. Here flow of these shear blocks is greatly enhanced by the air flow into the hopper. Most importantly this fragmented air flow even when low in magnitude will eliminate the formation of adverse interstitial fluid pressure gradients. Reiterating despite this flow being small in magnitude it is almost impossible to generate practical low pressure air flow through the hopper contents whenever the hopper contents are subject to a peaked or initial stress field.

A further advantage of air sparging this flow promoting effect is self correcting. Notably a sluggish flowing coal will be exposed to a longer period of air flow so facilitating increased moisture reduction of the flow bulk. This partial surface moisture reduction may generate significant improvements in the flow properties. However such increased aeration times must be well within the limits determined by the spontaneous combustion characteristics of the stored coal and which does not impart any significant loss of calorific value or coking property.

OTHER TECHNIQUES TO EFFECT COMPACTION

Before closing this discussion it is appropriate to briefly discuss other possible techniques to effect compaction of fine coal discharges from bins. Such compaction is possible using a number of mechanical devices which subject the flowing coal to compaction. These devices, when used in different situations particularly when handling dry materials, may be used as a flow promotion devices. Possible compaction devices hence include vibrated bin activators, large diameter screw feeders with compaction zones (Fig. 7) and moving hopper side wall systems (Fig. 8) to name just a few.

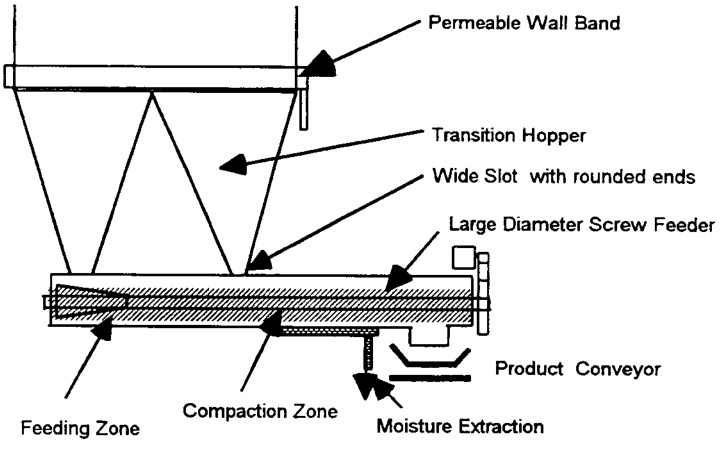

Fig. 7 - Bin incorporating a combined feeding and compaction zone large diameter screw feeder

Techniques to effect compaction using a screw feeder, refer Fig. 7, include decreasing the flight pitch or diameter in combination to increasing the hub diameter (Carson,1987 and Bridge, 1987). Other techniques include omitting a screw flight, plug formation (missing flights at the end of the screw) and the use of a beach or contraction in the screw casing transport volume (Carson, 1988;Womack, 1987; Stuart-Dick, 1991). Here it may be noted the simplest technique to generate a beach is to arrange an inclination in the screw casing base. In all cases the transition must be smooth and impart no ledge or obstruction to the flowing fine coal.

In regard to the moving hopper side wall system, as shown in Fig. 8, the transport volume below the hopper outlet proper (selected for flow reliability to have a large span) only experiences a slight and controlled reduction in the transport volume so imparting controlled compaction of the discharging material.

As one observes compaction by these post hopper discharge systems is associated with retardation of the flowing material. Such retardation of coal flow is rort with danger as over compaction, system blinding and flow obstructions can easily occur. Unfortunately, once a flow obstruction or coal plug occurs flow can only be reinitiated by removing, usually manually, the hopper contents and obviously the blockage. It is also expected these systems would attract very high initial and maintainance costs.

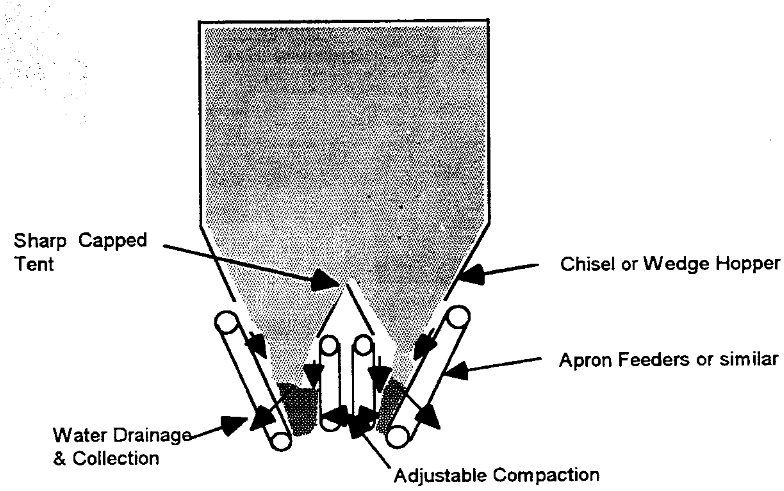

Fig. 8 - Moving hopper side wall feeding and compaction system

CONCLUSION

This paper initially highlights the vast difference in bin consolidation pressure distributions between the initial and flow conditions. This discussion, especially of the consolidation pressures in the cylinder, suggests the opportunity for partial moisture removal from the bin contents. The extent of which can be maximised by suitable selection of bin parameters.

A further consequence of the predicted consolidation stress distributions is that bulk solids must dilate to flow. This dilation, in hoppers with inappropriately selected design parameters effectively nullifies the compaction imparted in the bin cylinder. The same also causes the formation of adverse interstitial pressure gradients which severely retard the flow of fine damp coal. Fortunately, these flow retarding two phase effects can be easily and at relatively low cost be eliminated by injecting low pressure high volume air into the discharging hopper contents. This flow enhancing air flow has the potential to simultaneously effect partial moisture reduction. The same is also shown to attract reliable and stable flow promotion in contrast to other mechanical based flow promotion and compacting devices.

The favourable flow characteristics associated with stable low friction lined transition hoppers feeding onto to wide belt feeders warrants widespread application for the reliable discharge of fine damp coal products. This application can be reinforced by selecting optimal hopper design parameters selected for each storage situation on a case by case basis and by installing air sparging facilities. Such improvements to the storage container will generate considerably enhanced container discharge characteristics without attracting excessive initial and maintainance cost. It is planned by the author, in association with a successful progressive engineering project company and a coal mine operator, to validate the claimed benefits in a future ACARP funded industry collaborative project. This project will also identify the benefit of optimising complete storage container design when handling adverse fine damp coal products. This application is in response to ongoing fine coal handling difficulties within the industry as reflected in the recently published ACARP research priorities (ACARP, 1996) an improved coal handling. Obviously this planned project will aim to prove this technology on a scale consistent with reliable coal flow, typical actual plant throughputs subject to actual operating conditions at minimal financial risk to the individual coal producer.

REFERENCES

Arnold, P C, McLean, A G and Roberts, A W, 'Bulk Solids Storage Flow and Handling', *TUNRA*, University of Newcastle, 1981

Australian Coal Association Research Program, 'Annual Report - ACARP Research Priorities for 1996/97', 6.1 (ii) p56

Bridge, D.T. and Carson, J. W., 'How to Design Efficient Screw and Belt Feeders for Bulk Solids', *Proc. Int'l Powder and Bulk Solids Handling & Processing Conference*, Rosemont, Ill, 1987, 23p

Carson, J.W. and Dick, D.S., 'Seals Improve Coal Flow into a Pressurised Environment', *Power Engineering'*, 1988, pp 24 - 27.

Carson, J.W., 'Designing Efficient Screw Feeders', *Powder and Bulk Engng* Dec. 1987, pp 32 – 42

Chamberlain, M. and McLean, A.G., 'Brown Coal Handling: Experience, Difficulties and Solutions', *Proc. 2nd Int'l Conference on Bulk Materials Storage, Handling and Transportation*, Wollongong, July 1986, pp 205 - 210.

De Lazzari, R., 'The Performance of an Air Permeated Bin', Unpublished BE thesis, Dept of Mechanical Engng, University of Wollongong, 1981

Johanson, J. R., 'Two Phase - Flow Effects on Solids Processing and Handling', *Chem. Engn Sci*, 1979, pp 77 – 86

Lobb, A., 'Investigation into the Performance of Hoppers Utilising Permeable Wall Linings', *Unpublished BE thesis*, Dept of Mechanical Engng, University of Wollongong, 1995

McLean, A. G., 'Fluid Phase Interactions in Solids Flow', Proceedings *CHEMECA Annual Conference*, Melbourne University, Sept. 1984.

Reed, G. B. and Johanson J. R., 'Feeding Calcine Dust with a Belt Feeder at Falconbridge', *Jnl Engng for Industry, Trans ASME*, Vol 95, No 1 , 1973, pp 72-74

SAA, 'Loads on Bulk Solids Containers', *AS 3774*, 1996

Stuart-Dick, D. and Carson, J.W., 'Feeding Solids into a Fluidized Bed Combustor', *Powder Handling and Processing*, Vol 3, No 4, Nov. 1991, pp 343 - 345.

Willis, G. J., 'Interstitial Gas Pressures During Flow of Simple Bulk Solids from a Plane Flow Bin', *Unpublished BE thesis*, Dept of Mechanical Engng, University of Wollongong, 1978

Winkler, W. A., 'The Bouganville 975 tph Feeder', Jnl for Engng for Industry, *Trans ASME*, Feb 1973, pp 27 - 30.

Womack, W., Tuffs, W. and Carson, J.W., 'Feeding Coal into a Pulverizer at Monsanto's Soda Springs Plant', *Proc. Intl Powder and Bulk Solids Handling & Processing Conference*, Rosemont, Ill, 1987